

Magnetic cycles of solar-type stars with different levels of coronal and chromospheric activity – comparison with the Sun

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Abstract. The atmospheric activity of the Sun and solar-type stars is analysed involving observations from HK-project at the Mount Wilson Observatory, the California and Carnegie Planet Search Program at the Keck and Lick Observatories, and the Magellan Planet Search Program at the Las Campanas Observatory. We show that for stars of F, G and K spectral classes, the cyclic activity, similar to the 11-yr Solar cycles, is different: it becomes more prominent in K-stars. Comparative study of solar-type stars with different levels of the chromospheric and coronal activity confirms that the Sun belongs to stars with the low level of the chromospheric activity and stands apart among these stars by the minimum level of the coronal radiation and minimum flux variations of the photospheric radiation.

Key words: Sun: activity, stars: solar-type, stars: late-type, stars: activity, stars: HK-project.

1 Introduction

The study of magnetic activity of the Sun and solar-type stars is of fundamental importance for astrophysics. This activity of the stars leads to the complex of composite electromagnetic and hydrodynamic processes in their atmospheres. Local active regions, which are characterized by a higher value of intensity of the local magnetic field, are: plagues and spots in photospheres, *CaII* flocculae in chromospheres and prominences in coronas.

It is difficult to predict the evolution of each active region in details. However, it has long been established that the total change of active areas integrated over the entire solar or stellar disk is cyclical not only in solar

activity but in stellar activity too (Baliunas et al. 1995; Morgenthaler et al. 2011; Kollath and Olah 2009; Bruevich and Kononovich 2011).

It is well known that the duration of the 11-yr cycle of solar activity (Schwabe cycle) ranges from 7 to 17 years according to a century and a half of direct solar observations.

Durations of chromospheric activity cycles, found for 50 stars of late spectral classes (F, G and K), vary from 7 to 20 years according to HK-project observations.

The HK-project of Mount Wilson observatory is one of the first and still the most outstanding program of observations of solar-type stars (Baliunas et al. 1995; Lockwood et al. 2007). One of the most important results was the discovery of 11-yr cycles of activity in solar-type stars.

Currently, there are several databases that include thousands of stars with measured fluxes in the chromospheric lines of $CaII$, see (Wright et al. 2004; Isaacson and Fisher 2010, Arriagada 2011, Garcia et al. 2010, Garcia et al. 2010), but only for a few tens of stars the periods of magnetic activity cycles are known (Baliunas et al. 1995; Radick et al. 1998; Lockwood et al. 2007; Morgenthaler et al. 2011; Olah et al. 2009).

In our work, we consider the following databases of observations of solar-type stars with known values of S -index:

1. HK-project – the program in which the Mount Wilson "S value" was first defined. The Mount Wilson "S value" (S -index, S) became the standard metric of chromospheric activity – the basic value with which all future projects of stellar chromospheric activity observations are compared and calibrated.

2. The California and Carnegie Planet Search Program which includes observations of approximately 1000 stars at Keck and Lick observatories in chromospheric $CaII H$ and K emission cores. S -indexes of these stars are converted to the Mount Wilson system, see Wright et al. 2004. From these measurements, median activity levels, stellar ages, and rotation periods from general parameterizations have been calculated for 1228 stars, ~ 1000 of which have no previously published S-values.

3. The Magellan Planet Search Program which includes Las Campanas Observatory chromospheric activity measurements of 670 F, G, K and M main sequence stars of the Southern Hemisphere. S -indexes of these stars are also converted to the Mount Wilson system, see Arriagada (2011).

The aims of our paper are: (1) - a study of the place of the Sun among stars with different levels of chromospheric and coronal activity belonging to

the main sequence on the Hertzsprung-Russell diagram; (2) - a comparative analysis of chromospheric, coronal and cyclic activity of the Sun and solar-type stars of F, G and K spectral classes.

2 The place of the Sun among the solar-type stars with different levels of chromospheric and coronal activity

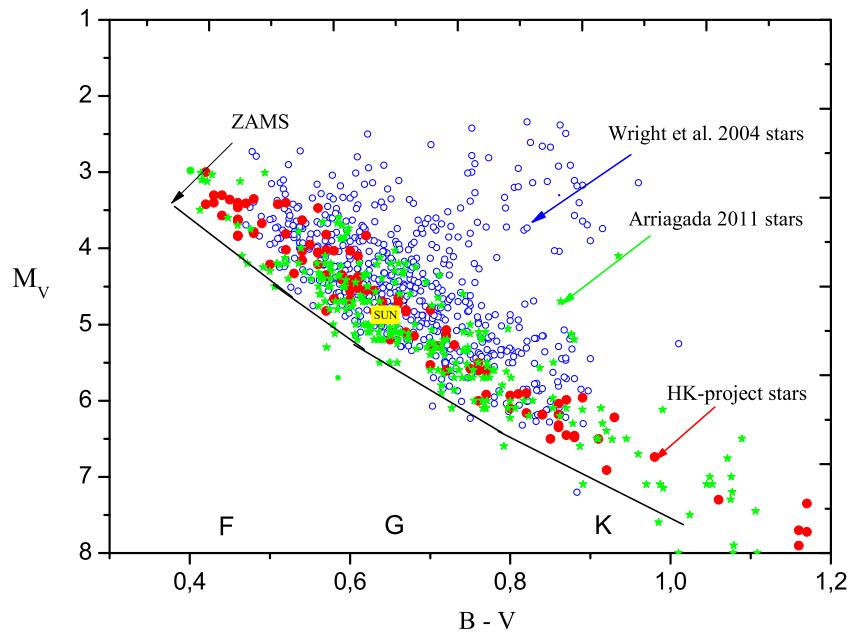


Figure 1: The Sun among the solar-type stars from different observational Programs on the Hertzsprung-Russell diagram.

In Figure 1, the Sun and stars from different observed samples are presented on the Color-Magnitude Hertzsprung-Russell diagram. There are 1000 solar-type stars from Wright et al. 2004, observed in Program of Planet

Search (blue circles); 660 solar-type stars from Arriagada (2011) observed in Magellan Planet Search Program (green circles) and 110 solar-type stars and the Sun from Baliunas et al. 1995, observed in the Mount Wilson HK-project (red circles). The solid line represents the Zero Age Main Sequence (ZAMS) on the Hertzsprung-Russell diagram.

Stars which are close to the ZAMS in Figure 1 have the lowest age among all other stars: $\log(\text{Age}/\text{yr})$ is about 8 - 8.5. The older the star is, the farther it is from the ZAMS. Ages of stars in the Figure 1 varies from 10^8 to 10^{10} years.

We can also see that some stars significantly differ from the Sun by the absolute magnitude M_V and color indices ($B - V$).

In different samples of stars from Planet Search Programs, some observers included a number of subgiants with a larger values of magnitudes M_V among the solar-type stars belonging to the main-sequence. We try to exclude them from our analysis.

In Figure 2, one can see that stars have significantly different values of S -index, which determines their chromospheric activity. According to Isaacson et al. 2010, the mean levels of chromospheric activity (corresponding to the uniform Mount Wilson S -index) for stars of the spectral class F are higher than that of the G-stars. On the other hand, for stars of K and M spectral classes, mean levels of chromospheric activity are also higher than that of G-stars.

We cannot see the close relationship of chromospheric activity of stars from our samples versus the color index in Figure 2.

For the large statistical sample – 2600 stars of the California Planet Search Program – the lower envelope of chromospheric activity level S_{BL} (S -index of Basic Level) was defined as a function (polynomial fit) of $B - V$ for main-sequence stars over the color range $0.4 < B - V < 1.6$, see Isaacson et al. 2010.

We show the S_{BL} dependence in Figure 2. It is seen that the Basic chromospheric activity Level S_{BL} begins to rise when $B - V > 1$. Isaacson et al. 2010 believed that this increase of S_{BL} is due to decrease of continuum flux for redder stars: S -value is defined as the ratio of H and K $CaII$ emission to the nearby continuum.

It can be noted that the level of chromospheric activity of the Sun is slightly below than the average level of chromospheric activity of the stars belonging to the main sequence.

In solar-type stars of late spectral classes, X-rays are generated by the

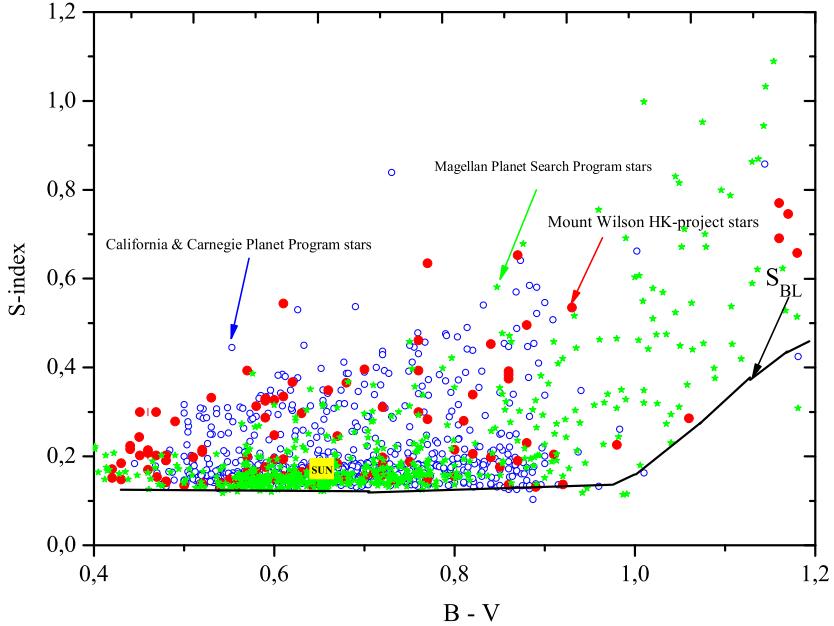


Figure 2: Chromospheric activity of F, G, K and M stars from three observational Programs.

magnetically confined plasma known as the corona (Vaiana et al. 1981), which is heated by the stellar magnetic dynamo. The observed decrease of the X-ray emission between pre-main sequence young stars and older stars can be attributed to the rotational spin-down of a star, driven by mass loss through a magnetized stellar wind (Skumanich 1972).

A relationship between stellar rotation and X-ray luminosity L_X was first described by Pallavicini et al. 1981.

In Figure 3 we show the L_X/L_{bol} versus P_{rot} for stars from the catalog of stars, the details of which are presented in Wright et al. 2011, and for the stars of the HK-project. In Write et al. 2011 there was done conversion of all X-ray luminosities of the stars of a catalog of 824 stars to the ROSAT 0.1-2.4 keV energy band. The selected data of X-ray luminosities L_X/L_{bol} of 80 HK-project stars was also taken from the ROSAT All-Sky Survey, see Bruevich et al. 2001. This sample also includes the Sun using the values of

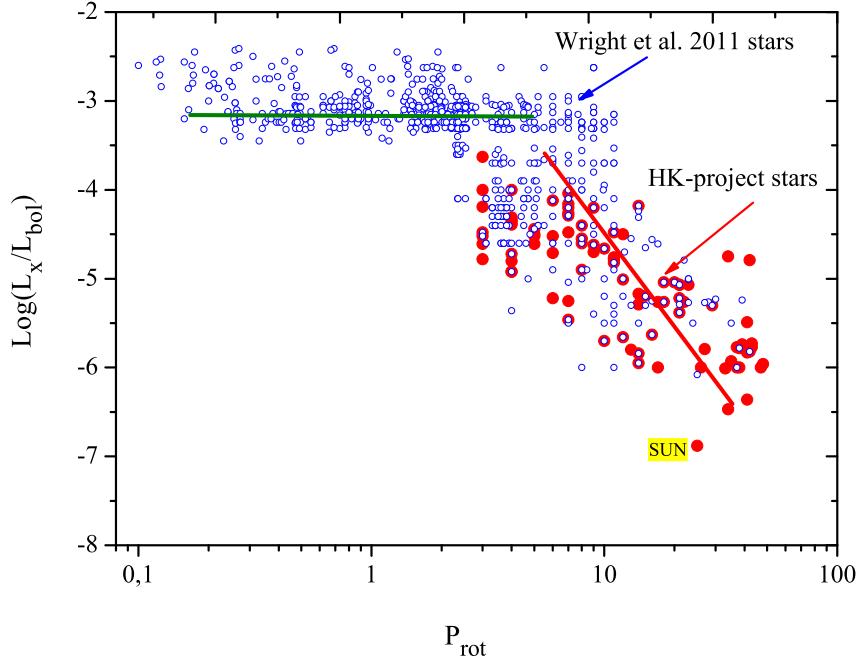


Figure 3: X-ray to bolometric luminosity ratio plotted against rotation period.

$\log L_X/L_{bol} = -6.24$ and $P_{rot} = 26.09$. Figure 3 demonstrates that there are two main regimes of coronal activity: a linear regime where activity increases with decreasing the rotation period, and a saturated regime where the X-rays luminosity ratio is constant with $\log(L_X/L_{bol}) = -3.13$, see Wright et al. 2011.

The HK-project stars which are not enough young and active are belong to the stars of linear regime in Figure 3. We can see that the Sun confirms its unique place among solar-type stars: it has almost the lowest level of X-rays luminosity among all the stars.

Below in Figure 7b we also show the place of the solar coronal activity among the coronal activity of stars of the HK-project. It can be noted the fact that the Sun is at the place with absolutely lowest level of coronal activity among solar-type stars.

It should be noted that solar photometric radiation changed very little

in the activity cycle, less than 0.1 %. The monitoring of the photometric and chromospheric H and K $CaII$ emission data series of stars similar to the Sun in age and average activity level showed that there is an empirical correlation between the average stellar chromospheric activity level and the photometric variability. In general, more active stars show larger photometric variability. The Sun is significantly less variable than indicated by the empirical relationship, see Shapiro et al. 2013. It was found that on a long time scale the position of the Sun on the diagram of photometric variability versus chromospheric activity changes is not constant in time. So Shapiro et al. 2013 suggested that the temporal mean solar variability might be in agreement with the stellar data.

But at present we can see that the Sun confirms its unique place among solar-type stars: its photometric variability is unusually small. This is confirmed in Lockwood et al. 2007: the photometric observations at the Lowell observatory of 33 stars of the HK-project revealed the fact that the photometric variability of the Sun during the cycle of magnetic activity is much less than the photometric variability of the other HK-project stars.

3 Observations of HK-project stars

It can be noted that among the databases of observations of solar-type stars with known values of S -index the sample of stars of HK-project was selected most carefully in order to study the stars which are analogs of the Sun.

Moreover, unlike different Planet Search Programs of observations of solar-type stars, the Mount Wilson Program was specifically developed for the study of solar-type cyclical activity of the main-sequence F, G and K-stars (single) which are the closest to the "young Sun" and "old Sun".

The duration of observations more than 40 years during the HK-project has allowed to detect and explore the cyclical activity of the stars, similar to 11-yr cyclical activity of the Sun. First O. Wilson began this program in 1965. He attached great importance to the long-standing systematic observations of cycles in the stars. The fluxes in passbands 0.1 nm wide and centered on the $CaII H$ and K emission cores have been monitored in 111 star of spectral type F2-K5 on or near main sequence on the Hertzsprung-Russell diagram (Baliunas et al. 1995; Radick et al. 1998; Lockwood et al. 2007).

Mount Wilson S -index is the relationship of radiation fluxes in the centers

of emission lines H and K (396,8 nm and 393,4 nm) to radiation fluxes in the near-continuum (400,1 and 390,1 nm) - is considered now as a sensitive indicator of the chromospheric activity of the Sun and the stars.

For HK-project the stars were carefully chosen according to those physical parameters, which were most close to the Sun: cold, single stars-dwarfs, belonging to the main sequence. Close binary systems are excluded.

The results of the joint observations of the HK-project radiation fluxes and periods of rotation gave the opportunity for the first time in stellar astrophysics to detect the rotational modulation of the observed fluxes (Noyes et al. 1984). This meant that on the surface of the star there are inhomogeneities those were living and evolving in several periods of rotation of the stars around its axis. In addition, the evolution of the periods of rotation of the stars in time clearly pointed to the fact of existence of the star's differential rotations similar to the Sun's differential rotations.

The authors of the HK-project with the help of frequency analysis of the 40-year observations have discovered that the periods of star's 11-yr cyclic activity vary little in size for the same star (Baliunas et al. 1995; Lockwood et al. 2007). The durations of cycles vary from 7 to 20 years for different stars. The stars with cycles represent about 30 % of the total number of studied stars.

4 Cyclic activity of HK-project stars. From periodogram to wavelet analysis.

The evolution of active regions on the star on a time scale of about 10 years determines the cyclic activity similar to the Sun.

For 111 HK-project stars the, periodograms were computed for each stellar record in order to search for activity cycles, see (Baliunas et al. 1995). The significance of the height of the tallest peak of the periodogram was estimated by the false alarm probability (FAP) function, see Scargle (1982). The stars with cycles were classified as follows: if for the calculated $P_{cyc} \pm \Delta P$ the FAP function $\leq 10^{-9}$ then this star is of "Excellent" class (P_{cyc} is the period of the cycle). If $10^{-9} \leq FAP \leq 10^{-5}$ then this star is of "Good" class. If $10^{-5} \leq FAP \leq 10^{-2}$ then this star is of "Fair" class. If $10^{-2} \leq FAP \leq 10^{-1}$ then this star is of "Poor" class.

About 50 of 111 stars were identified with varying degrees of reliability

as the stars with regular cycles which periods P_{cyc} which are varied from 7 to 20 years.

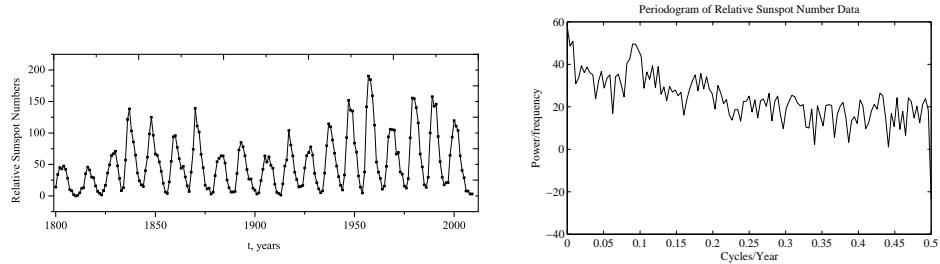


Figure 4: Yearly averaged relative sunspot numbers, observations from 1800 to 2009 – at left; the periodogram of the yearly averaged relative sunspot numbers for 1800 to 2009 observations – at right.

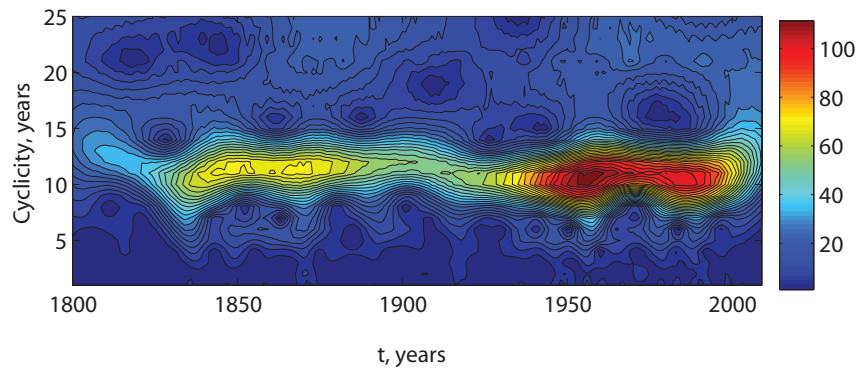


Figure 5: Wavelet analysis of the yearly averaged relative sunspot numbers. Complex Morlet wavelet 1.5-1. Observations from 1800 to 2009.

In (Baliunas et al. 1995; Radick et al. 1998; Lockwood et al. 2007) the regular chromospheric cyclical activity of HK-project solar-type stars were studied through the analysis of the power spectral density with the Scargle's periodogram method (Scargle 1982). Periods of HK-project stars activity cycles similar to 11-yr solar activity cycle were calculated. The significance of the height of the tallest peak of the periodogram was estimated by the false alarm probability (FAP) function. In the case when the calculated $P_{cyc} \pm \Delta P$ the FAP function $\leq 10^{-9}$ this star is of "Excellent" class. Among these 50 stars with cycles they have found only 12 stars and the Sun to be characterized by the cyclic activity of the "Excellent" class.

We illustrate the method of cyclic period calculation with Scargle's periodogram technique on the example of the Sun. We obtained the periodogram of the yearly averaged relative sunspot number (or Wolf number) for observations conducted in 1800 – 2009.

In Figure 4 (left part) we present the relative sunspot number yearly averaged data set. It is known that the direct observations of sunspots were made only since 1850, and from 1800 to 1850 years the sunspots data were taken from indirect estimates. This fact, as we will see below in Figure 5, affects the quality of the wavelet analysis from 1800 to 1850 years.

The Scargle's periodogram of the relative sunspot number for 1800 - 2009 data set is presented in Figure 4 (right part). This periodogram shows that there is a peak at approximately 0.1 cycles/year, which indicates a period of approximately 10 years.

Our illustration of the Scargle's periodogram method shows that, unfortunately, this method allows us only to define a fixed set of the main frequencies (that determines the presence of significant periodicities in the series of observations). In the case where the values of periods change significantly during the interval of observations, the accuracy of determination of periods becomes worse. It is also impossible to obtain information about the evolution of the periodicity in time.

In Figure 5 we show the results of wavelet analysis of the same sunspot number yearly averaged data set.

Figure 5 confirms the known fact that the periods of the solar activity cycle is about 11-yr in the XIX century and about 10 yr in the XX century. It is seen that the quality of the wavelet pictures in the first half of the XIX century is much worse than later in the XX century when the era of direct observation began.

According to different solar observations, the mean value of the period of

solar activity cycle in the twentieth century is about 10.2 years. It is also known that the abnormally long 23-rd cycle of solar activity ended in 2009 and lasted about 12.5 years. All of this is shown in relative sunspot numbers wavelet picture in Figure 5. Thus, we can see that the value of period of the main cycle of solar activity for the past 150 years is not constant and varies by 15-20 %.

In Kollath and Olah 2009 it has been tested and used different methods, such as short-term Fourier transform, wavelet, and generalized time-frequency distributions, for analyzing temporal variations in timescales of long-term observational data which have information on the magnetic cycles of active stars and that of the Sun.

Wavelet analysis is becoming a common tool in present time for the analysis of localized variations of power within a time series. By decomposing a time series into time-frequency space, one is able to determine the dominant modes of variability and how those modes vary in time. The choice of wavelet is dictated by the signal or image characteristics and the nature of the application. Understanding the properties of the wavelet analysis and synthesis, you can choose a mother wavelet function that is optimized for your application. Thus, we choose a complex Morlet wavelet which depends on two parameters: a bandwidth parameter and a wavelet center frequency.

The multi-scale evolution in the solar activity was found in Kollath and Olah 2009 with used of wavelet and generalized time-frequency analysis. The observed features in the time-frequency history of the Sun were analyzed with wavelet methods. The time-frequency analysis of multi-decadal variability of the solar Schwabe (11-yr) and Gleissberg (secular) cycles during the last 250 years from Sunspot Number records showed that one cycle (Schwabe) varies between limits, while the longer one (Gleissberg) continually increases. In Kollath and Olah 2009 by analogy from the analysis of the longer solar record, the presence of a long-term trend may suggest an increasing or decreasing of multi-decadal cycle that is presently unresolved in the stellar records of short duration.

In Olah et al. 2009 the study of the time variations of the cycles of 20 active stars based on decades-long photometric or spectroscopic observations with method of time-frequency analysis was done. They found that the cycles in the sun-like stars show systematic changes, the same phenomenon we can see in the cycles of the Sun.

Olah et al. 2009 found that fifteen stars definitely show multiple cycles, the records of the rest are too short to verify a timescale for a second cycle.

For 6 HK-project stars: HD 131156A, HD 131156B, HD 100180, HD 201092, HD 201091 and HD 95735 the multiple cycles were detected with used of wavelet-analysis.

HD 131156A shows variability on two time scales: the shorter cycle is about 5.5-yr, a longer-period variability is about 11 yr. For HD 131156B only one long-term periodicity has been determined. For HD 100180 the variable cycle of 13.7-yr appears in the beginning of the record; the period decreases to 8.6-yr by the end of the record. The results in the beginning of the dataset are similar to those found by Baliunas et al. 1995, who found two cycles, which are equal to 3.56 and 12.9-yr. The record for HD 201092 also exhibits two activity cycles: one is equal to 4.7-yr, the other has a timescale of 10-13 years. The main cycle seen in the record of HD 201091 has a mean length of 6.7-yr, which slowly changes between 6.2 and 7.2-yr, a shorter, significant cycle is found in the first half of the record with a characteristic timescale of 3.6-yr. The stronger cycle of HD 95735 is 3.9-yr, which is slightly shorter (3.4-yr), a longer, 11-yr cycle is also present with a smaller amplitude.

We showed that complex Morlet wavelet 1.5 - 1 can most accurately determine the dominant cyclicity as well as its evolution in time in solar data sets at different wavelengths and spectral intervals (Bruevich et. al 2013).

We have applied the wavelet analysis for partially available data in form of pictures (the curves of variation of S -index with time in Baliunas et al. 1995 and Lockwood et al. 2007) to 5 HK-project stars with cyclic activity of the "Excellent" class: HD 10476, HD 81809, HD 103095, HD 152391, HD 160346 and to the star HD 185144 with no cyclicity.

We used the complex Morlet wavelet 1.5 - 1 which can most accurately determine the dominant cyclicity as well as its evolution in time in solar data sets at different wavelengths and spectral intervals (Bruevich et. al 2013).

So for these 6 stars we have used partially available observation data of S -index for 1965-1992 observation sets (Baliunas et al. 1995) and for 1985-2002 observations (Lockwood et al. 2007). We used the detailed graphical time dependencies of S -index, each point of the record of observations, which we processed in this paper using wavelet analysis technique, corresponds to three months averaged values of S -index.

We hoped that wavelet analysis can help us to study the temporal evolution of chromospheric activity cycles of the stars. Tree-month averaging also helps us to avoid the modulation of observational data by star's rotations similarly to the case of the Sun.

In Figure 6 we present our results of the cycles of 6 stars:

HD 81809 has a mean length of 8.2-yr, which slowly changes between 8.3-yr in the first half of the record and 8.1-yr in the middle and the end of the record while Baliunas et al. 1995 found 8.17-yr.

HD 103095 has a mean length of 7.2-yr, which slowly changes between 7.3-yr in the first half of the record, 7.0-yr in the middle and 7.2-yr in the end of the record while Baliunas et al. 1995 found 7.3-yr.

HD 152391 has a mean length of 10.8-yr, which slowly changes between 11.0-yr in the first half of the record and 10.0-yr in the end of the record while Baliunas et al. 1995 found 10.9-yr.

HD 160346 has a mean length of 7.0-yr which is not changes during the record in agreement with Baliunas et al. 1995 estimated 7.0-yr.

HD 10476 has a mean length of 10.0-yr in the first half of the record, then the length sharply changes to 14-yr, while Baliunas et al. 1995 found 9.6-yr. After changing of high amplitude cycle's period from 10-yr to 14-yr in 1987 the low amplitude cycle remained exist at 10.0-yr period - we can see two activity cycles. Baliunas et al. 1995 estimated HD 10476 cycle as 9.6-yr.

HD 185144 has a mean length of 7-yr which changes between 8-yr in the first half of the record and 6-yr in the end of the record while Baliunas et al. 1995 haven't found the well-pronounced cycle.

In Olah et al. 2009 the multiple cycles were found for the stars HD 13115A, HD 131156B, HD 93735 for which in Baliunas et al. 1995 haven't been found any cycles; for the stars of "Excellent" class HD 201091 and HD 201092 the cycle's periods found in Baliunas et al. 1995 were confirmed and also the shorter cycles (similar to solar quasi-biennial) were determined.

Olah et al. 2009 have concluded that all the stars from their pattern of cool main-sequence stars have the cycles and most of the cycle lengths change systematically. But the stars of "Excellent" class have relatively constant cycle lengths - for these stars the cycle's periods calculated in Baliunas et al. 1995 and cycle's periods found with use of wavelet analysis are the same.

The long-term behavior of the sunspot group numbers have been analyzed using wavelet technique by Frick et al. 1997 who plotted the changes of the Schwabe cycle (length and strength) and studied the grand minima. The temporal evolution of the Gleissberg cycle can also be seen in the time-frequency distribution of the solar data. According to Frick et al. 1997 the Gleissberg cycle is as variable as the Schwabe cycle. It has two higher amplitude occurrences: first around 1800 (during the Dalton minimum), and then around 1950. They found very interesting fact - the continuous decrease

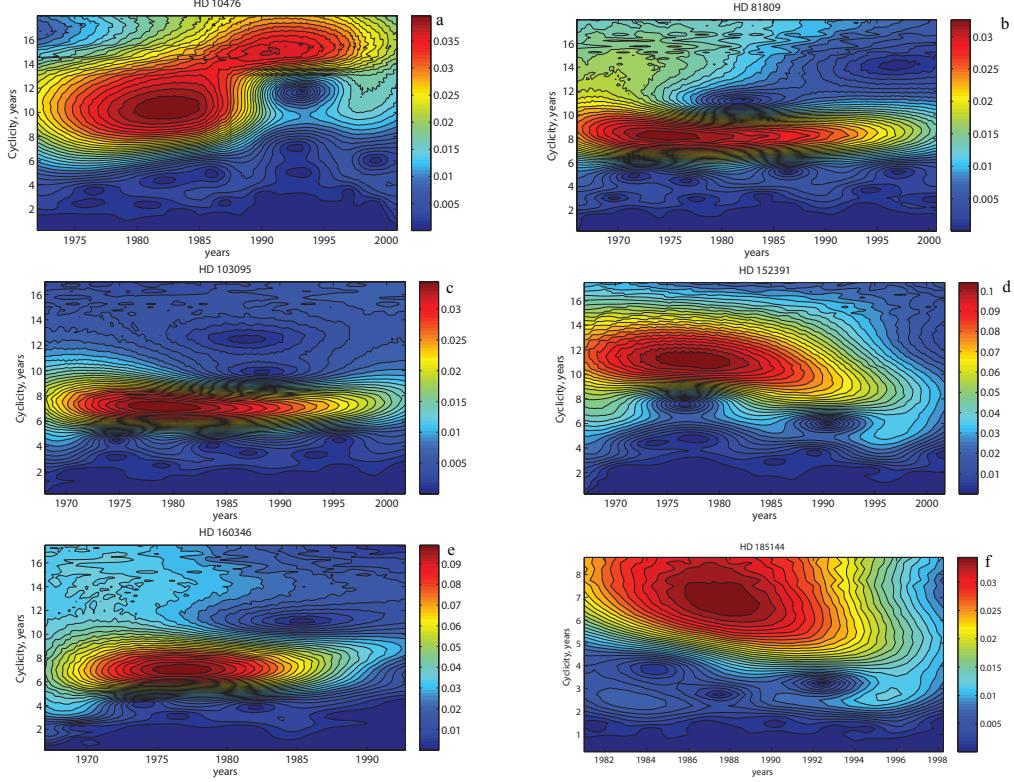


Figure 6: Wavelet analysis of HK-project stars. Complex Morlet wavelet 1.5-1. Observations from 1969 to 2002: (a) HD 10476, (b) HD 81809, (c) HD 103095, (d) HD 152391, (e) HD 160346, (f) HD 185144.

in the frequency (increase of period) of Gleissberg cycle. While near 1750 the cycle length was about 50 yr, it lengthened to approximately 130 yr by 1950.

In the late of XX century some of solar physicists began to examine with different methods the variations of relative sunspot numbers not only in high amplitude 11-yr Schwabe cycle but in low amplitude cycles approximately equal to half (5.5-yr) and fourth (quasi-biennial) parts of period of the main 11-yr cycle, see (Vitinsky et al. 1986). The periods of the quasi-biennial cycles vary considerably within one 11-yr cycle, decreasing from 3.5 to 2 yrs, and this fact complicates the study of such periodicity using the method of periodogram estimates.

Using the methods of frequency analysis of signals the quasi-biennial cy-

cles have been studied not only for the relative sunspot number, but also for 10.7 cm solar radio emission and for some other indices of solar activity ((Bruevich et al. 2013, Bruevich and Yakunina 2015). It was also shown that the cyclicity on the quasi-biennial time scale takes place often among the stars with 11-yr cyclicity, see Bruevich and Kononovich 2011.

The cyclicity similar to the solar quasi-biennial was also detected for the solar-type stars from the direct observations. In Morgenthaler et al. 2011 the results of direct observation of magnetic cycles of 19 solar-type stars of F, G, K spectral classes within 4 years were presented. The stars of this sample are characterized by masses between 0.6 and 1.4 solar mass and by rotation periods between 3.4 and 43 days. Observations were made using NARVAL spectropolarimeter (Pic du Midi, France) between 2007 and 2011. It was shown that for the stars of this sample τ Boo and HD 78366 (the same of the Mount Wilson HK-project) the cycle lengths derived by chromospheric activity (Baliunas et al. 1995) seem to be longer than those derived by spectropolarimetry observations of Morgenthaler et al. 2011. They suggest that this apparent discrepancy may be linked to the different temporal sampling inherent to the two approaches, so that the sampling adopted at Mount Wilson may not be sufficiently tight to unveil short activity cycles. They hope that future observations of Pic du Midi stellar sample will allow them to investigate longer time scales of the stellar magnetic evolution.

For the solar-type F, G and K stars according to *Kepler* observations, "shorter" chromosphere cycles with periods of about two years have also been found, see Metcalfe et al. 2010, Garcia et al. 2010.

We assume that precisely these quasi-biennial cycles were identified in Morgenthaler et al. 2011: τ Boo and HD 78366 are the same of the HK-project, these stars have the cycles similar to the quasi-biennial solar cycles with periods of a quarter of the duration of the periods defined in Baliunas et al. 1995.

Note, that in case of the Sun, the amplitude of variations of the radiation in quasi-biennial cycles is substantially less than the amplitude of variations in main 11-yr cycle. We believe that this fact is also true for all solar-type stars of the HK-project and in the same way for τ Boo and HD 78366.

The quasi-biennial cycles cannot be detected with the Scargle's periodogram method. But methods of spectropolarimetry from (Morgenthaler et al. 2011) allowed detecting the cycles with 2 and 3-yr periods. Thus spectropolarimetry is more accurate method for detection of cycles with different periods and with low amplitudes of variations.

So, the need for wavelet analysis of HK-project observational data is dictated also by the fact that the application of wavelet method to these observations will help: (1) to find the cyclicities with periods equal to half and a quarter from the main high amplitude cyclicity; (2) to clarify the periods of the high amplitude cycles and to follow their evolution in time; (3) to find still other stars with cycles for which the cycles were not determined using the method of periodogram due to strong variations of the period as in case of HD 185144.

The analysis of cyclic activity of solar-type stars using Scargle's periodogram method in (Baliunas et al. 1995) and wavelet analysis simultaneously showed that the selection of stars into classes according to the quality of their cycles ("Excellent", "Good", "Fair" and "Poor") is very important moment in the study of stellar cycles.

Wavelet analysis helped us to understand why the stars of "Fair" and "Poor" classes are differ from the stars of "Excellent" and "Good" classes: the main peak on their periodograms is greatly expanded due to strong variations of the cycle's duration.

As it turned out, the differentiation of stars with cycles onto classes "Excellent" , "Good", "Fair" and "Poor" is very important: the stars with the stable cycles "Excellent" and "Good" and the stars with the unstable cycles "Fair" and "Poor" relate to different groups in the graphs of dependencies S versus $(B - V)$, $\log L_X$ versus $(B - V)$, P_{cyc} versus Age, see Figure 7 and Figure 8 below.

5 Chromospheric and coronal activity of HK project stars of different spectral classes with cycles

Processes, that determine complex phenomena of stellar activity and covering practically the whole atmosphere from the photosphere to the corona, occur differently among solar-type stars belonging to different spectral classes.

The Mount Wilson HK project observational data allow us to study the solar-type cyclic activity of stars simultaneously with their chromospheric and coronal activity. The selected data of X-ray luminosities $\log L_X$ of 80 HK-project stars is taken from the ROSAT All-Sky Survey, see Bruevich et

al. 2001.

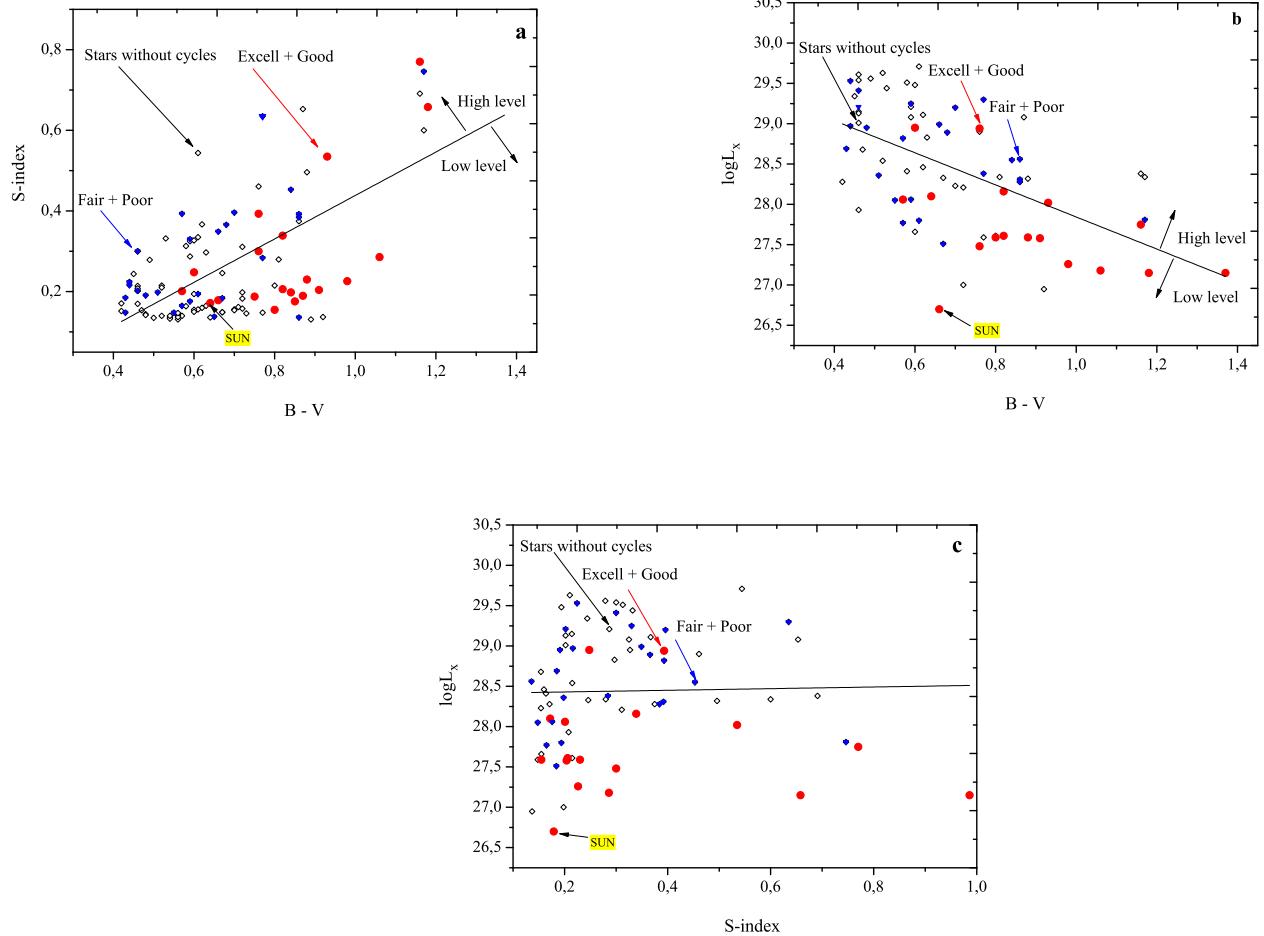


Figure 7: HK-project stars. Observations from 1969 to 1994 yrs. (a) S versus $(B - V)$, (b) $\log L_x$ versus $(B - V)$, (c) $\log L_x$ versus S .

As noted earlier (Baliunas et al. 1995), the average chromospheric activity of the stars, or rather the value of $\log S$ varies (increases) with the increase of the color index $(B - V)$, see Figure 2, Figure 7a.

Our linear regression analysis of HK-project stars showed that there is a relation which is described by the following formula:

$$S = -0.10 + 0.530 \cdot (B - V) \quad (1)$$

Let us denote the right part of the relation (1) as $F(B - V)$.

We consider the stars which have $S > F(B - V)$ to be characterized by the high level of chromospheric activity, and stars with $S \leq F(B - V)$ — by the low level of chromospheric activity, see Figure 7a.

Next, we have analyzed all 110 stars from the HK-project and the Sun to determine which kind of the level of chromospheric activity corresponds to one or another star. We will consider these results further in the comparative analysis of stars of different spectral classes, see Table 1.

For 80 stars, the coronal radiation of which we know from the ROSAT data, we also do linear regression analysis and obtain the following relationship between X-ray luminosity, normalized to the bolometric luminosity, and color index $(B - V)$:

$$\log L_X = 29.83 - 1.99 \cdot (B - V) \quad (2)$$

Let us denote the right hand side of the relation (2) as $P(B - V)$. By analogy with the analysis of the chromospheric activity of stars, we consider the stars with $\log L_X > P(B - V)$ to be characterized by the high level of coronal activity, and stars with $\log L_X \leq P(B - V)$ — by the low level of coronal activity, see Figure 7b.

As noted above, in the case of chromospheric activity a direct correlation takes place: with the increase of the color index $(B - V)$ the average value of chromospheric activity (S) of stars increases. But in the case of X-ray radiation of stars from $(B - V)$ the inverse correlation takes place: with the increase of the color index $(B - V)$, the average value $\log L_X$ decreases, see Figure 7a, 7b.

Note that most of stars, characterized by increased chromospheric activity, have also increased coronal activity. About 15 % of stars, including the Sun, are characterized by coronal activity that is significantly lower than the value which should correspond to its chromospheric activity, see Figure 7c.

Figures 7a, 7b demonstrate that stars with cycles of "Excellent" and "Good" classes are mostly characterized by low level of chromospheric and coronal activity (about 70 %), as opposed to stars with cycles of "Fair" and "Poor" classes which are mostly characterized by high level of chromospheric and coronal activity (about 75 %).

The existence or absence of a pronounced cyclicity, as well as the quality of the identified cycles (belonging to classes "Excellent", "Good", "Fair", "Poor"), for F, G and K stars varies significantly.

Table 1: Comparative analysis of cycles of stars and the quality of their cyclicities for stars of different spectral classes.

Interval of spectral classes	F2 -F9	G2 -G9	K0 -K7
$\Delta(B - V)$	0.42 -0.56	0.57 -0.87	0.88 -1.37
Total number of stars in spectral interval	39	44	27
Number of stars with known values L_X	27	29	24
Relative number of stars with increased coronal activity	60%	48%	41%
Relative number of stars with increased chromospheric activity	56%	39%	60%
relative number of stars with chromospheric activity cycles	25%	40%	72%
Quality of chromospheric cycles "Excellent+Good"/"Fair+Poor"	0/10	7/10	14/4

Bruevich et al. (2001) noted the difference between the stars of "Excellent", "Good", "Fair" and "Poor" classes from a position of presence and degree of development of under photospheric convective zones of stars of different ($B - V$).

Thus, we can note here (illustrated below in Table 1) that the quality of chromospheric activity cycles (the ratio of the total number of stars belonging to classes with a well-defined cyclicity "Excellent" + "Good" to the number of stars with less than a certain cyclicity "Fair" + "Poor") essentially differs for stars of different spectral classes F, G and K.

Different tests of the dependency of the cycle period (with durations in various time scales from seconds in the asteroseismic analysis to several yrs in Dynamo processes studies) on different parameters of solar-type stars have been performed, see Morgenthaler et al. 2006, Garcia et al. 2010, Garcia et al. 2014, Mathur et al. 2012, Metcalfe et al. 2010.

We have analyzed the dependence of the star magnetic cycle duration on its age. Cycle durations were taken from Baliunas et al. 1995. Stel-

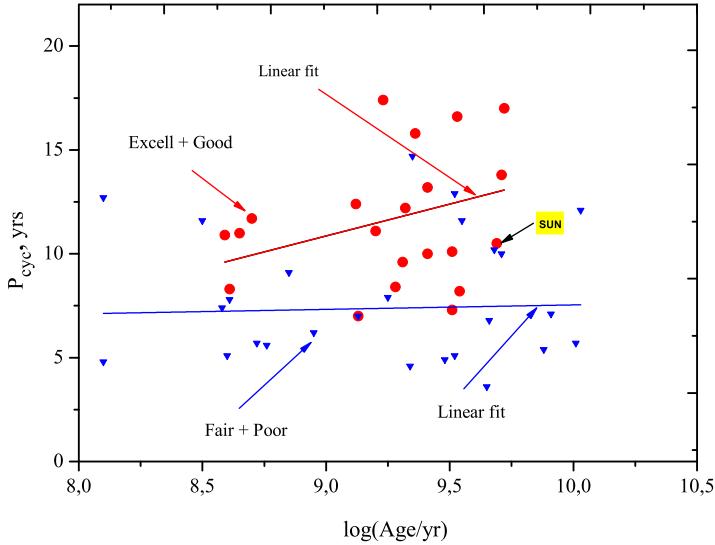


Figure 8: P_{cyc} versus stellar age.

lar ages were calculated according to Wright et al. 2004 as a function of chromospheric activity.

In Figure 8, the dependence of P_{cyc} versus age of stars is shown. The scatter of points around the linear regression line is very large. For stars with cycles of "Excellent" + "Good" classes with the increase of the age (or various parameters connected with the age) the duration of cycles increases by about 20 % with an increase of $\log(\text{Age}/\text{yr})$ from 8.5 to 10. The stars with cycles of "Fair" + "Poor" classes show no dependence of P_{cyc} on age. So the problem of determination of P_{cyc} as accurately as possible, using frequency-time (wavelet) analysis, becomes very actual.

6 Conclusions

- We believe that the nature of the cyclic activity of solar-type stars is very similar to the Sun's one: along with main cycles there are quasi-biennial cycles. Periods of these quasi-biennial cycles evolve during one

main (11-yr cycle) from 2 to 3.5 yrs that complicates their detection with the periodogram technique. Our conclusion is supported by the direct observation of cycles with the duration 2-3 yrs for τ Boo and HD 78366 by Morgenthaler et al. (2011) and earlier detection of cycles with duration 11.6 and 12.3 yrs by Baliunas et al. (1995) for the same stars.

- The quality of the cyclic activity, similar to the solar 11-yr one, is significantly improved (from "Fair + Poor" to "Excellent + Good") in G and K-stars as compared to F-stars. The F-stars 11-yr cyclicity (detected only in every fourth case) is determined with a lower degree of reliability.
- The chromospheric activity of HK-project stars is maximal for stars of the spectral class K, see Table 1. This fact is consistent with the idea that the chromospheric activity is formed in inner parts of the stellar convective zone, see Bruevich et al. (2001). G-stars (and the Sun) are of less chromospheric activity among the stars studied here, the increased activity of atmospheres of F-stars is also characterized by enhanced chromospheric activity, slightly less than that of K-stars. This conclusion is consistent with the analysis of Isaacson et al. 2010. The Basic chromospheric activity Level S_{BL} from Isaacson et al. 2010 begins to rise when $B - V > 1$. This increase of S_{BL} is because of a decrease of the continuum flux for redder stars.

We confirm that in case of chromospheric activity a direct correlation takes place, in the case of X-ray radiation of stars versus $(B - V)$ the inverse correlation takes place.

- The level of chromospheric activity of the Sun is consistent with that of HK-project stars, which have well-defined cycles of activity ("Excellent + Good") and similar color indexes. On the other hand, the coronal activity of the Sun is significantly below that of the coronal activity of G-stars of the HK-project and other observational Programs.
- The coronal activity is also more pronounced in stars of the spectral class F, due to their total increased atmospheric activity (as compared to stars of spectral classes G and K), and is not associated with under photospheric convective zones in the practical absence of chromospheric cycles.

- Now it's of great interest to find planets of habitable zone which is the region around a star where a planet with sufficient atmospheric pressure can maintain liquid water on its surface. We believe that the close attention should be paid to the unique characteristics of our Sun: a very low level of variability of the photospheric radiation simultaneously with a very low level of coronal radiation. Probably, the search for extraterrestrial life should be conducted simultaneously on the "planets of habitable zone" and on the "stars comfortable for life", such as the Sun.

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